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BEARING CAPACITY OF STRIP FOOTING RESTING ON DUNE SANDS STABILIZED BY GROUTING WITH LIME–SILICA FUME MIX

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ABSTRACT

Extensive dune sand deposits cover specific areas of Iraq. Dune sands are often an environment hazard during strong winds and sand storms particularly in the summer months. A little research has taken place to study the characteristics and the behavior of dune sands.

An extensive laboratory testing program was carried out to study the geotechnical properties and the behavior of dune sands. The tests include moisture content, classification, compaction, relative density, direct shear, chemical tests. Also, loading tests were carried out on footing model of strip shape (3.2 × 33) cm rested on natural dune sand. The effectiveness of adding different percentages of lime-silica fume mix was studied. Silica fume (SF) and lime-silica fume (L-SF) mix has been used for stabilizing and considering their effects on the dune sands. The improvement technique adopted in this study represents an attempt to stabilize the dune sands by grouting the soil by a slurry of lime-silica fume material with water. For grouting the dune sands around the stabilized area, a 1000 ml grout pump was used as a liquid tank of the lime-silica fume mix and the maximum pressure which can be applied by pumping the grout into the dune sands with the help of a grout pump is about 25 kPa.

Four categories were studied to stabilize dune sand before and after loading test and for each category, the effectiveness of grouting was

investigated; the effect of injection hole spacing and depth of grout was investigated too.

Finally, the dune sand underneath and around a footing is injected by a slurry of lime-silica fume, there will be an increase in the ultimate bearing capacity of about 19 times. The bearing capacity increases with increase of depth of grouting holes around the footing area due to increase in L-SF grout, for a stabilizer grout percent of (33% (3L : 4SF) with 67% water by total mixture weight).

Key words Dune Sand, Lime, Silica Fume, Loading, Stabilized, Grouting

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INTRODUCTION

A single dune can be defined as a mound or hill of sand, which rises to a single summit. They are accumulations of windblown sand, which change their position or their shape due to wind action as long as their surface consists of loose granular material of appropriate size. The real problem of sand dunes is their creep that affects development of projects; such as highways, railways, irrigation and drainage canals, agricultural lands, and other projects. Dunes are causing a decrease in the efficiency and increase in the maintenance costs for these projects.

Zoght (1978) stated that the mobile sand dunes are heaps of moving sand, of different sizes. They occupy large areas in many parts of the world and are generally areas of zero productivity, often threatening to cover inhabited localities e.g. roads, farms, water channels and other resources.

Regardless of how stabilization is approached or methods classified, Shakatreh and Authman (1984) and Shakatreh (1985) demonstrated that methods of sand dune stabilization depend on two principles:

i. Mechanical fixation: This aims to reduce the velocity of the wind to make it lose its ability to erode; and/or prevent wind reaching the sand surface.

ii. Biological fixation: This type of fixation aims to stabilize and fix sand dunes; improve the local environmental conditions and to convert sand dunes into productive lands.

Grouting is a quite familiar technique in the field of civil engineering, especially in foundation engineering. The technology of grouting finds applications in almost all the fields of foundation engineering such as seepage control in rock and soil under dams, advancing tunnels, cut off walls etc., (Nonveiller, 1989).

The primary purpose of grouting is to fill the voids of the formation material by replacing the existing fluids with the grout and thereby improving the engineering properties of the medium especially reducing the permeability. Grouting is effective in both sand and silt deposits. Grouts are liquid suspensions or solutions that are injected into the soil mass to improve its behavior. Such liquids can permeate into the void space of the soil and bind the soil particles together.

Al-Refeai and Al-Suhaibani (1998) carried out a study to investigate the resilient behavior of polypropylene fiber-reinforced sand. Triaxial, California bearing ratio

(CBR), and resilient modulus tests were conducted on fiber-reinforced sand as well as unreinforced sand, and the results compared. The optimum fiber content was found to be 0.4% by weight. The triaxial shear strength of the fiber-reinforced sand specimens revealed that there were two modes of failure, fiber-sand bond failure and fiber failure, and the internal friction angle depended on the mode of failure. Synthetic fiber-reinforced sand has greater CBR values than those of unreinforced sand. The effect of fiber reinforcement on the resilient modulus, M_R, values was investigated in terms of resilient modulus model parameters. In general, the model parameters revealed a decreasing effect of both the deviator and confining stresses on the M_R values up to 0.2 to 0.4% fiber content. The permanent deformation of sand specimens was reduced by the addition of fibers, and the permanent deformation decreased as fiber content increased.

Badescup et al. (2008) proposed macro-engineering using tactical technologies that stabilize and vegetate barren near-coast sand dune fields with seawater. Seawater that would otherwise, as commonly postulated, increase the Earth–ocean volume. Anthropogenic saturation of the ground with pumped seawater should fix widespread active sand dune fields in deserts (such as the westernmost Sahara). Seawater extraction from the ocean, and its deposition on dune sand, is made via solar-powered pipeline. Stabilization of one major erg in Mauritania was evaluated as a case study.

Ameta and Hiranandani (2013) presented a study of stabilization of dune sand with ceramic tiles wastage as admixture. All the California Bearing Ratio tests were conducted at maximum dry density and optimum moisture content as arrived from Standard Proctor Test. Direct shear tests were also performed. The main objective of this experimental study was to obtain an economical stabilized mix of ceramic tiles wastage and dune sand so that largely and cheaply available dune-sand be used for various construction purposes.

Panwar and Ameta (2013) studied the strength characteristics of dune sand of

western Rajasthan stabilized with cheap and readily available material like lime and bentonite. Dune sand which covers a big part of western Rajasthan is weak in strength and possesses problems in construction of road. The investigation was an attempt to stabilize this soil with the aid of lime and bentonite. Standard Proctor test, unconfined compressive strength, in addition to some preliminary tests were conducted for assessing the suitability of limebentonite mix with dune sand.

The purpose of the present research is to assess the suitability of dune sands as construction materials, moreover, such a purpose is considered beneficial in assessing appropriate methods for soil stabilization or ground improvement and to assess the suitability of dune sands as subgrade layer for carrying roads.

EXPERIMENTAL WORK

This work is basically a laboratory oriented investigation. The consistency and other physical properties of the dune sand were studied by a series of tests. In this study, lime-silica fume mix is suggested to overcome the problems of dune sands.

Four materials are used in this study; soil (dune sand), lime, silica fume and water. The specification of each material is as follows:

Soil (dune sand)

Dune sand samples were obtained from Baiji area in Salah-Aldeen governorate North of Baghdad in Iraq. Due to a medium wind velocity there (as usual in this region,

November, 2013); the grey, dry soil samples were packed into double plastic bags to avoid falling of the fine loose parts of the sample.

In situ field density (ρ_{field}) was obtained by sand-cone test. One of the most common field density test methods is the 'Sand-Cone Method' (ASTM D 1556-00) and this method is applied in the study. A summary of the average results from the field-density tests is shown in Table 1.

Table 1 Results of field density (ρ_{field}) by sand-cone method.

Soil Property		Sample No.		
		1	**2**	**3**
1	Sample field density, ρ_{field} (gm/cm^3)	1.641	1.669	1.577
2	Average field density, (gm/cm^3)	1.629 gm/cm^3		

Table 2 Summary of Baiji sand dunes properties.

Soil properties		Baijisand dunes
Total density, ρ_t	(gm/cm^3)	1.629
Water content, w	%	1.23
Atterberg limits on Passing No. 40	L.L.	–
	P.L.	–
	P.I.	NP
Group Index	G.I.	0.0
Specific Gravity	G_S	2.665
Particle Size Distribution by Wet Sieving	%Gravel	0.00
	% Sand	91.0
	% Fines	9.00
Coefficient of uniformity	C_U	2.56
Coefficient of curvature	C_C	1.60
Classification of Soil	USCS	SP
	AASHTO	A-3
Max. of dry density, ($\rho_{d.max}$) (gm/cm^3)	Standard compaction	1.682
	Modified compaction	1.785
Optimum moisture content, %(O.M.C)	Standard compaction	13.6%
	Modified compaction	11.0%
Relative density, %	$\rho_{d.min}$, (gm/cm^3)	1.485
	$\rho_{d.max}$, (gm/cm^3)	1.706
	e_{max}	0.795
	e_{min}	0.562
	Dr	59.5
Direct shear test	ϕ, degree	32°
	c, kPa	0

The moisture content (%w.c) for the soil studied was determined according to (ASTM D 2216-00). Moisture-density relationship was determined by means of the standard and modified Proctor compaction test. The tests were performed in accordance with (ASTM D 698-00, method A) and (ASTM D 1557-00, method A) standards, respectively. The results of compaction test are summarized in Table 2 and moisture- density relationships are shown in Figure 1. The direct shear test was

carried out in accordance with the procedure given in ASTM D 3080-98. A standard direct shear box of 60 mm square specimen was prepared in steel box with different initial water contents.

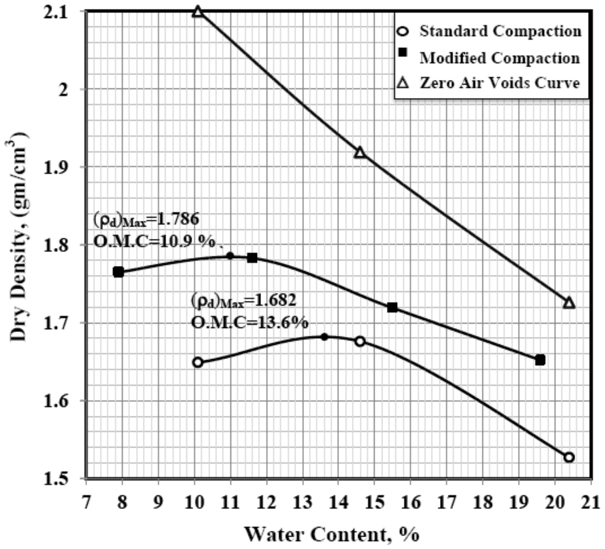


Figure 1 Standard and modified compaction curves.

The lime material (L)

Calcium hydroxide (slaked lime) is most widely used for stabilization. Calcium oxide (Hydrated lime) may be more effective in some cases, therefore the product of Lorestan Industrial for Hydrated Lime Company. The results of chemical and physical properties of the lime used are shown in Table 3.

Table 3 Chemical and physical results of hydrated lime tests.

Physical and Chemical Properties	Results
Loss on ignition (L.O.I)	26.74
Silicon dioxide (SiO_2) + Grays	5.62
Iron oxide (Fe_2O_3)	0.44
Aluminum oxide (Al_2O_3)	0.46
Calcium oxide (CaO)	66.08
Magnesium oxide (MgO)	0.10
Sulfur trioxide (SO_3)	0.72
Specific gravity, G_s	2.30
Density , gm/cm^3	0.60

Silica fume material (SF):

In this study, a grey-colored densified silica fume is used. It is a pozzolanic material which has a high content of amorphous silicon dioxide and consists of very fine spherical particles. Silica fume was used as an additive material to improve soil properties. The product used is called MEYCO®MS610 which contains extremely fine (0.1-0.2 µm) latently reactive silicon dioxide. The presence of this substance gives greatly improved internal cohesion, water retention and increased density when set. The additional crystal formation and the fineness of MEYCO MS610 produce a

significantly more dense set cement matrix. Chemical tests on this material. The results of the chemical analysis of this material are presented in Table 4.

All products of silica fume available are in densified silica fume type to make these products dense enough to be transported economically and be handled like Portland cement. The densification process greatly reduces the dust associated with the as-produced silica fume.

Table 4 Physical and chemical propertiesof silica fume tests.

Physical and Chemical Properties	Composition
SiO_2	> 85%
Fe_2O_3	< 2.5%
Al_2O_3	< 1%
CaO	< 1%
$K_2O + Na_2O$	< 3%
C (free)	< 4%
S	< 1%
Cl^{-1}	< 0.2%
L.O.I	< 6%
Specific gravity, G_s	2.25
Density, gm/cm^3	0.75
Moisture	< 2%
Specific Surface	~20 m^2/gr

Model Loading Tests

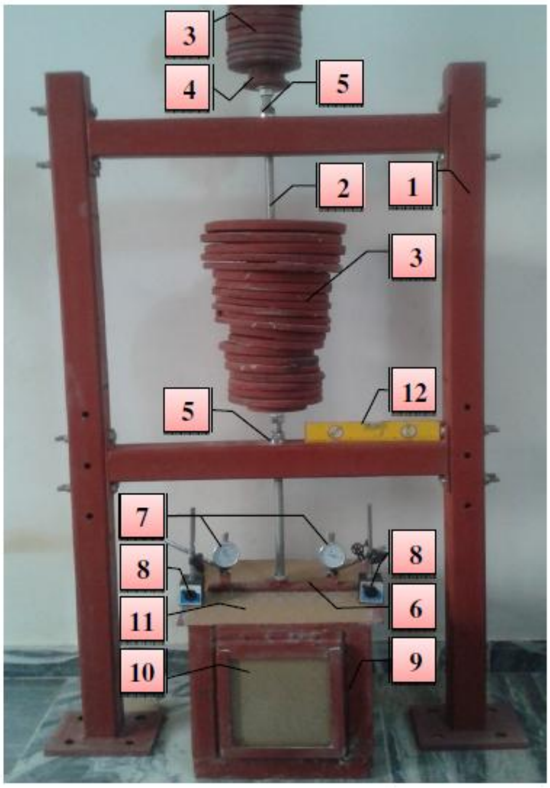
All model tests were conducted using the setup shown in Figure 2, which consists of steel loading frame, soil tank, bed of soil and grouting apparatus. The vertical load was applied to the model foundation by dead weights put in the axial shaft and two deformation dial gages with 0.01 mm sensitivity have been used for measuring displacements of the strip steel footing with a ratio of length/width as 10.3.

A loading frame was designed and manufactured to apply static vertical loads on the model footing. Details of the main features of the loading assembly are shown in Figure 3 a. Shallow footing model tests were carried out in a test box having dimensions of 36 × 36 cm in plan and 32 cm in depth. The front side of the container consists of a glass plate 22 cm in height, 25 cm in width and 1.6 cm in thickness. The size of the box was decided suitable for the size of footing and the range of load influence. Depending on Bossineq's approach, it is obvious from the figure that the effect of load acting on soil was very little at depth equal to 3B, i.e., the load equals to 0.05 q_o under the footing. Also at a distance of 1.5 B from the center of the footing, the pressure bulb gives the ratio of $(q/q_o) = 0.05$. Therefore, the selected dimensions were 36 × 36 × 32 cm as shown in Figure 3 b.

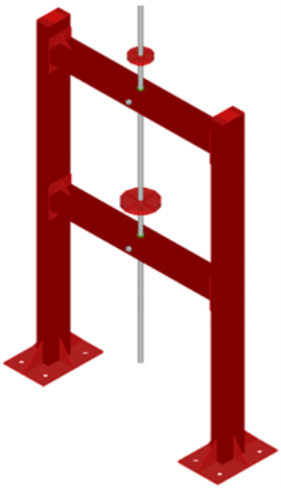
Strip footing model was used to fulfill the objectives of this work, to assess the suitability of sand dunes as subgrade layer for carrying roads and rail foundation, Figure 3 c. It was made from a steel plate 33 cm in length, 3.2 cm in width and 1.0 cm thickness.

Raining frame

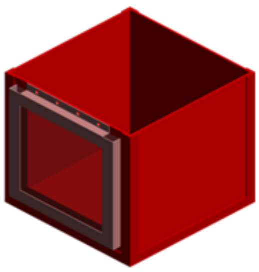
A simple frame was used for controlling and obtaining the specific density using the sand raining technique as shown in Figure 4. The frame consists of steel mechanical jack; the cone that is used to pour the sand was suspended at the connection end by means of a steel chain. The effect of falling height on the controlled density is shown in Figure 5. The required density that has been used in the tests is achieved at a height of fall equal to 40 cm.



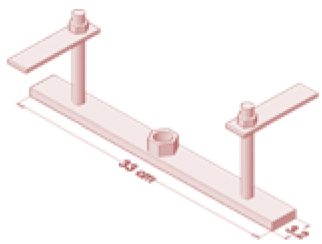
	Legend
1	Steel loading frame
2	Steel axial shaft
3	Dead loads
4	Loading disk
5	Control valve
6	Steel strip footing
7	Dail gauges, 0.01 mm accuracy
8	Magnetic holder
9	Steel box
10	Glass plate
11	Bed of sand dune
12	Bubble level



a. Loading frame



b. Box model



c. Footing model

Figure 3 The manufactured loading frame, steel box and the footing model.

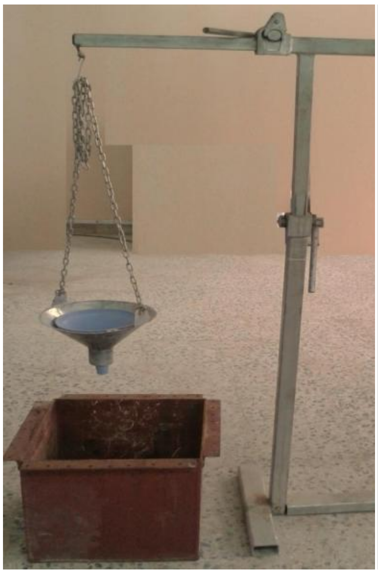


Figure 4 Raining frame.

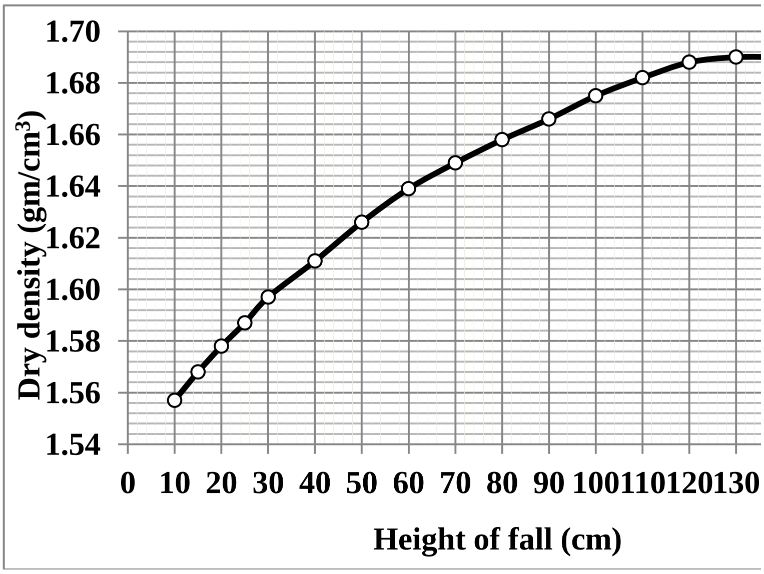


Figure 5 Relationship between dry density and height of fall.

Soil Stabilized with (L-SF) by Grouting:

To place the grout within the pores of the granular medium, previously prepared sand beds were grouted with L-SF grouting materials by using a grout pump to simulate the grouting operations in the field. The preparations of this type are described in details below:

Grout impregnation by pumping:

Predetermined quantity of L-SF was selected with a definite amount of water. The slurry was thoroughly mixed for 10 minutes at 3000 rpm using a standard stirrer. The grouting setup consists of a grout chamber, electrical pump, grouting nozzle (pvc pipe, 6 mm in diameter), pressure gage and regulating valve. The grouting nozzle was kept in position (at 5 cm above bottom level of tank) and the dune sand bed was prepared in a tank of size 36 × 36 × 32 cm at a dry density of 1.609 gm/cm^3 and an initial void ratio of 0.656. A dune sand was put in the tank by pouring through a funnel from a height of 0.4 m from the top of the sand dunes bed. Then the slurry (grout) was poured into the grout chamber. In order to reduce the possibility of settling of the grout in the grout chamber, an agitator was provided inside the grout chamber. Grout was pumped under an average pressure of 0.25 bar (25 kPa) into the prepared soil bed.

The grouted sample was kept for curing under moist condition for one day. Each soil sample was subjected to 350 kg load applied on a strip footing 3.2 cm width and the settlement was recorded.

An apparatus was designed for the purpose of this study as shown in Figure 6. The apparatus consists of two parts as follows:

1. Electric pump: Water pump was used as a grout pump of the lime-silica fume mix and the average pressure which can be applied by pump is about 25 kPa.
2. Injection pipe: The grout is injected into the soil through a pvc pipe which has a diameter of 6 mm with perforations (0.65 mm) in diameter. One side is closed and 24 perforations in around the surface (for depth 2B) and 36 perforations in four directions (for depth 3B) are made. The slurry flows through the perforations and penetrates the soil, as shown in Figure 7.

Figure 6 Grouting apparatus.

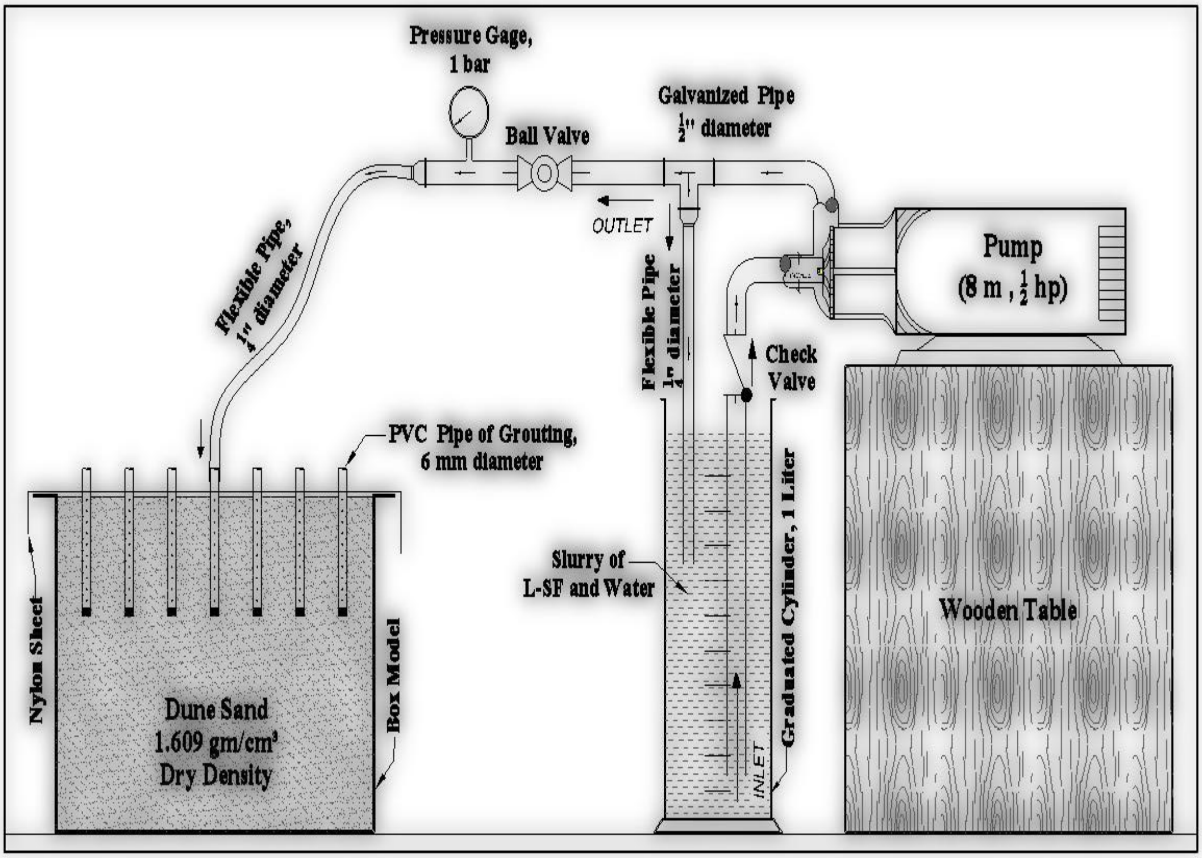


Figure 7 Grouting apparatus.

Selection of the percentages of (L-SF)

The percentages of L-SF were selected based on review of pertinent literatures, (Al-Jobouri, 2013). Four percentages were used, those were: 33% (1L : 4SF) with 67% water, 33% (2L : 4SF) with 67% water, 33% (3L : 4SF) with 67% water and 25% (1L: 4SF) with 75% water by total mixture weight with different spacing and depths of grouting pipes as illustrated in Figures 8 and 9 and Table 5.

Procedure of grouting the soil in the model

The following procedure was used for preparing the samples:

1. After completion of soil placing in steel box, the surface was leveled and checked by a bubble level. Then, it was covered with a nylon sheet to protect the soil bed from tarnishes.
2. The quantity of lime-silica fume slurry was prepared because the pozzolanic reaction between lime and silica fume causes aggregation of the slurried particles and close the pipe injection. Therefore, four percentages were used. Lime and silica fume were mixed to be homogenous, and grouted to the bed of soil at specified points following a uniform pattern, Figure 7.

Then a quantity of water 67% of the total weight was added to the mix for cases (1 to 24) and 75% for cases 25 to 32 as shown in Table 5.

The slurry was thoroughly mixed for 10 minutes at 3000 rpm using a standard stirrer. Injection pipe was penetrated through the soil to a desired depth then injection started by pumping under a pressure of 25 kPa. The control of grouting pressure is vital to the success of any grouting operation.

RESULTS OF MODEL TESTING

The allowable soil pressure of a shallow foundation is limited either by the net safe bearing capacity or the safe settlement-pressure. The design of shallow foundation on cohesionless soils is generally governed by the safe settlement pressure (Arora, 2009).

To investigate the behavior of dune sands improved by lime-silica fume grout, different model tests were performed on a shallow foundation resting on dune sands subjected to static vertical load.

The investigation focuses on the influence of the spacing of grouting holes and depth of grouting. Defining the ultimate bearing capacity from load tests by choosing a single value of q_{ult} to define “failure” of a shallow foundation is difficult as different locations along a stress-settlement curve will result in different values of q_{ult}.

In this work, the failure point is considered at settlement equal to 10% of the width of footing (B) as ASTM D194-94 recommended. Using the (0.1 B) method is more suitable in this work because type of failure in soil is "Punching shear failure", so it is easy to apply.

The analysis of results of all model tests regarding the applied stress and the corresponding settlement is illustrated in terms of load-settlement curves.

Model loading tests were carried out on dune sand as given in the testing program, to evaluate the bearing capacity of soil, taking into consideration the effects of the following factors:

1. Mixture percentage (L-SF with water).
2. Different spacings and depths of grouting points.

Loading tests on soil stabilized by grouting

In order to investigate the behavior of shallow foundation resting on stabilized dune sands, loading tests were carried out using strip footing model resting on dune sands prepared at natural density.

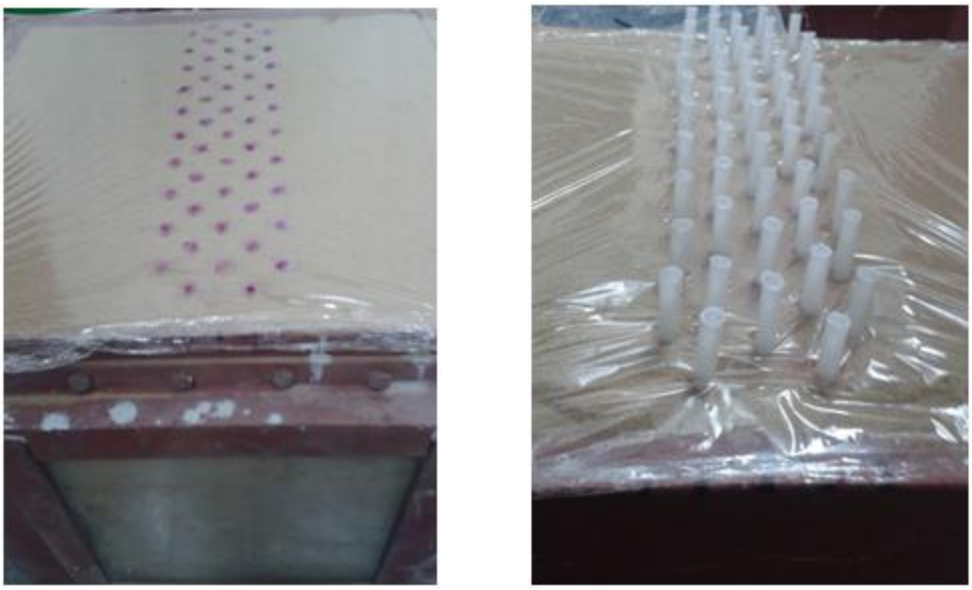


Figure 8 Spacing of grouted points in the soil.

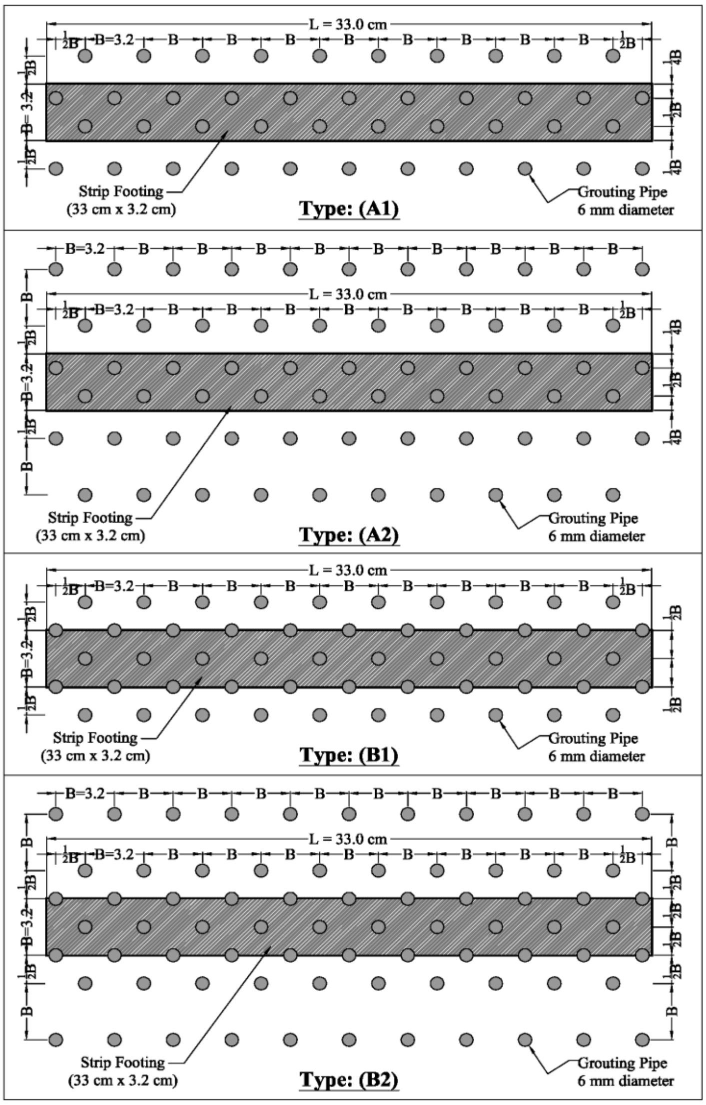


Figure 9 Different spacings and locations of grouting points.

Table 5 Cases studied for different spacings and depths of grouting points.

Cases	Mix presentation of grouting	Dry density of dune sand (gm/cm3)	Type of pipe array	No. of grouting pipes	Depth of grouting
Case (1)	33% (1 L : 4 SF) and 67% water by total mixture weight	1.609	A1	42	2B
Case (2)		1.609	A2	63	2B
Case (3)		1.609	B1	52	2B
Case (4)		1.609	B2	73	2B
Case (5)		1.609	A1	42	3B
Case (6)		1.609	A2	63	3B
Case (7)		1.609	B1	52	3B
Case (8)		1.609	B2	73	3B
Case (9)	33% (2 L : 4 SF) and 67% water by total mixture weight	1.609	A1	42	2B
Case (10)		1.609	A2	63	2B
Case (11)		1.609	B1	52	2B
Case (12)		1.609	B2	73	2B
Case (13)		1.609	A1	42	3B
Case (14)		1.609	A2	63	3B
Case (15)		1.609	B1	52	3B
Case (16)		1.609	B2	73	3B
Case (17)	33% (3 L : 4 SF) and 67% water by total mixture weight	1.609	A1	42	2B
Case (18)		1.609	A2	63	2B
Case (19)		1.609	B1	52	2B
Case (20)		1.609	B2	73	2B
Case (21)		1.609	A1	42	3B
Case (22)		1.609	A2	63	3B
Case (23)		1.609	B1	52	3B
Case (24)		1.609	B2	73	3B
Case (25)	25% (3 L : 4 SF) and 75% water by total mixture weight	1.609	A1	42	2B
Case (26)		1.609	A2	63	2B
Case (27)		1.609	B1	52	2B
Case (28)		1.609	B2	73	2B
Case (29)		1.609	A1	42	3B
Case (30)		1.609	A2	63	3B
Case (31)		1.609	B1	52	3B
Case (32)		1.609	B2	73	3B

Grouting underneath and around the footing

In this category, it is intended to study the effect of grouting underneath and around the footing to a distance of 1/2 B and B for four grid shapes as shown in Figure 9, where the pattern of holes in (A1) and (A2) represent holes below the footing in addition to row around the footing in (A1) and two rows in (A2).

Pattern (B1) is similar to (A1) but one additional row of grouting holes is used below the footing. Pattern (B2) is similar to (A2) but one additional row of holes is added below the footing.

Table 5 shows four groups of mixture percentage (L-SF with water) and eight cases to each group for different spacings and depths of grouting points.

Figures 10 to 15 show the load-settlement curves for footings resting on natural soils and soil stabilized with L-SF for all cases. The experiments were carried out to investigate the effect of hole spacing inside the footing area which consists of rigid steel plate (330×32×10) mm during loading test and after failure.

The stress-settlement curves shown in these figures reveal that a peak value of load per unit area, q, is never observed. The ultimate bearing capacity, q_{ult}, is defined as the point where (Change of settlement / Change of load per unit area, q) becomes the largest and almost constant thereafter. This type of failure in soil called "Punching shear failure". In this case, the failure surface never extends up to the ground surface.

The nature of failure in soil at ultimate load is a function of several factors such as the strength and the relative compressibility of soil, the depth of the foundation (D_f) in relation to the foundation width (B), and the width-to-length ratio (B/L) of the foundation. This was clearly explained by Vesic (1973) who conducted extensive laboratory model tests in sand. Therefore the (0.1 B) method is adopted in this work.

In these figures, ρ_d = 1.609 gm/cm^3 which represents the field density, ρ_d = 1.682 gm/cm^3 which represents the maximum dry density from compaction curve and ρ_d = 1.708 gm/cm^3 which represents the maximum dry density from relative density test.

Figure 16 shows grouting behavior for stabilized dune sands and the jet-grouting noticed after excavation and cleaning at the laboratory.

Results showed that the increase in the depth of grouting for injection points, increased the proportion of ultimate bearing capacity. The increasing in ultimate bearing capacity ranged between (762 – 2008)% as illustrated in Table 6. The increasing in ultimate bearing capacity is calculated as follows:

$$\text{\% Increasing in } q_{ult} = \frac{q_{ult} \text{ of treated sand} - q_{ult} \text{ of natural soil}}{q_{ult} \text{ of natural soil}} \times 100 \qquad (1)$$

Table 6 presents a summary of the results for ultimate bearing capacity calculated as the load corresponding to a settlement of 10% of model strip footing 3.2 mm wide.

The results show a convergence of the ultimate bearing capacity between types of spacing grouting (A1) and (A2), also between (B1) and (B2). Injection to a depth of 3B gave better results than the injection depth of 2B due to increase of soil strength and decrease in the settlement as a result of the increases in the angle of internal friction (ϕ) and cohesion (c).

Using L-SF as an additive does not maximize the strength of the stabilized soils only, but rather improve the global properties of the mixture. The observed relationship between the bearing pressure and settlement demonstrated a significant increase in the ultimate bearing capacity, as illustrated in Table 6, which showed the strength gain obtained with L-SF.

The added materials of L-SF play the major role in stabilization. Using this type of material is reflected in the improvements in terms of bearing capacity. Adding L-SF increases the ultimate bearing capacity, and then the bearing capacity generally, tends to remain constant. It can be noticed that the optimum grid spacing which showed the maximum load according to the failure criterion of (0.1 B) is for soil treated by case 21 which included 42 holes grout and soil treated by case 22 which included 63 holes of grout. It can be decided that the minimum case of hole grout (minimum L-SF grout) for economic application is maintained by case 21.

Table 6 Ultimate bearing capacity corresponding to a settlement of 10% of footing width

No	Case	Type of pipe array	No. of grouting pipes	Depth of grouting	Mix presentation of grouting	$q_{ult.}$, kPa	Increasing in $q_{ult.}$, (%)
1	Natural Soil	-	-	-	No grouting	13	-
2	Case (1)	A1	42	2B	33% (1 L : 4 SF) and 67% water by mixture weight	168	1192
3	Case (2)	A2	63	2B		169	1200
4	Case (3)	B1	52	2B		112	762
5	Case (4)	B2	73	2B		118	808
6	Case (5)	A1	42	3B		180	1285
7	Case (6)	A2	63	3B		208	1500
8	Case (7)	B1	52	3B		125	862
9	Case (8)	B2	73	3B		129	892
10	Case (9)	A1	42	2B	33% (2 L : 4 SF) and 67% water by mixture weight	185	1323
11	Case (10)	A2	63	2B		196	1408
12	Case (11)	B1	52	2B		136	946
13	Case (12)	B2	73	2B		140	977
14	Case (13)	A1	42	3B		213	1538
15	Case (14)	A2	63	3B		214	1546
16	Case (15)	B1	52	3B		154	1085
17	Case (16)	B2	73	3B		158	1115
18	Case (17)	A1	42	2B	33% (3 L : 4 SF) and 67% water by mixture weight	202	1454
19	Case (18)	A2	63	2B		213	1538
20	Case (19)	B1	52	2B		191	1369
21	Case (20)	B2	73	2B		196	1408
22	Case (21)	A1	42	3B		262	1915
23	Case (22)	A2	63	3B		274	2008
24	Case (23)	B1	52	3B		220	1592
25	Case (24)	B2	73	3B		227	1646
26	Case (25)	A1	42	2B	25% (3 L : 4 SF) and 75% water by mixture weight	158	1115
27	Case (26)	A2	63	2B		169	1200
28	Case (27)	B1	52	2B		136	946
29	Case (28)	B2	73	2B		141	985
30	Case (29)	A1	42	3B		190	1362
31	Case (30)	A2	63	3B		191	1369
32	Case (31)	B1	52	3B		154	1085
33	Case (32)	B2	73	3B		158	1115

It is clear to suggest that the optimum percentage of case 21 (33% (3L: 4SF) with 67% water by total mixture weight), can be recommended for Baiji dune sands.

Figures 17 to 20 show the relationships between the ultimate bearing capacity of strip footing and depth of grouting for different spacings of grouting points and different percentages of L-SF mixture. Figures 21 to 24 show similar relationships between the ultimate bearing capacity of strip footing and number of grouting points around the footing for different depths of grouting and different percentages of L-SF mix.

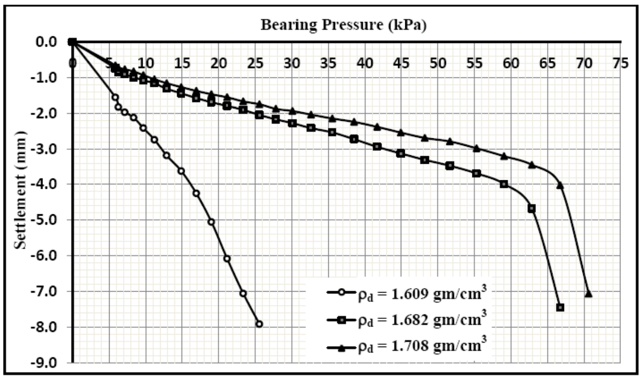
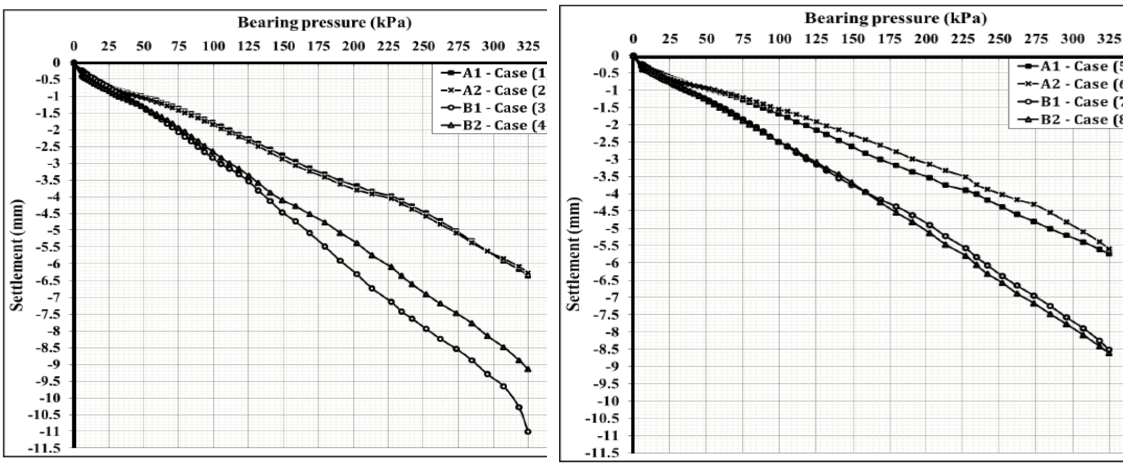


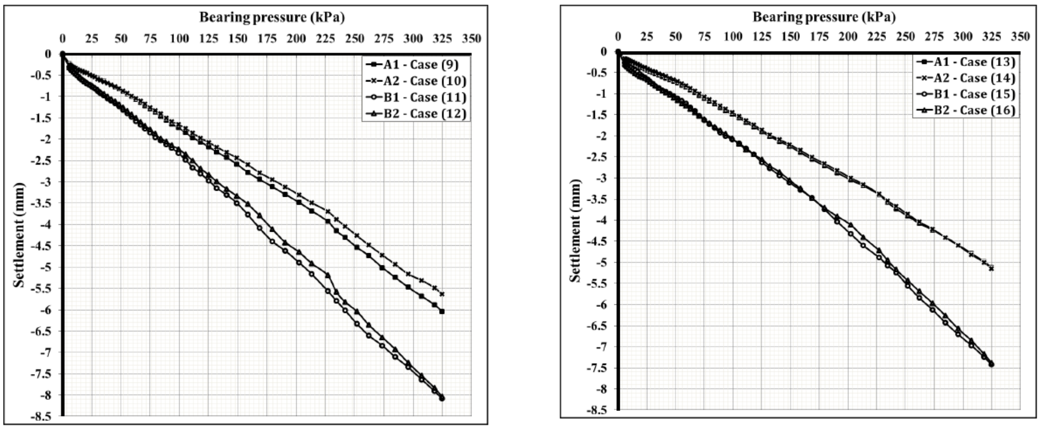
Figure 10 Bearing pressure-settlement curves for footing resting on natural Baiji dune sands of different densities.



A) For different spacings and (2B) depth of grouting points.

B) For different spacings and (3B) depth of grouting points.

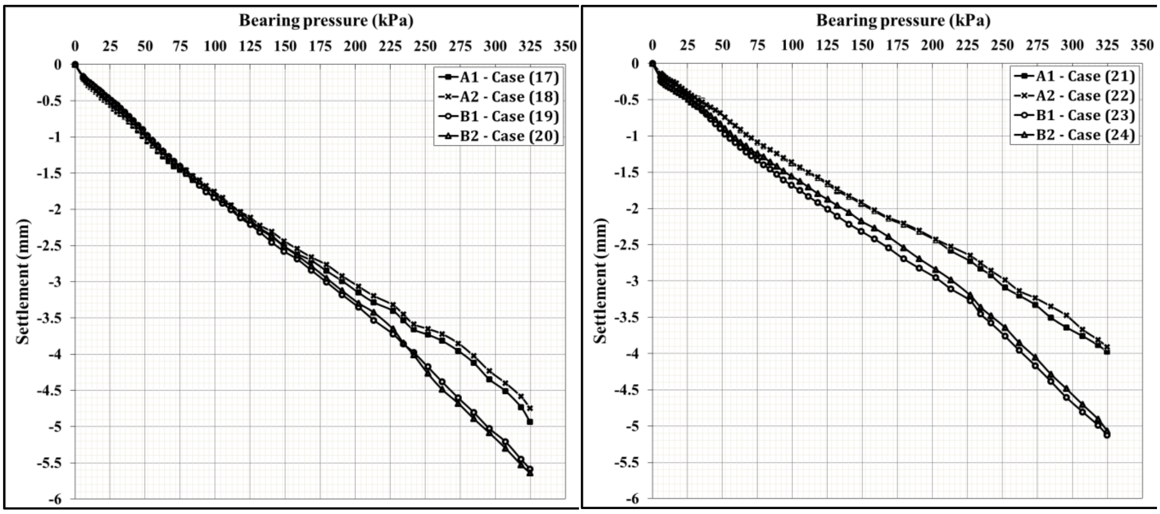
Figure 11 Bearing pressure-settlement curves of footing resting on dune sands stabilized by grouting with 33% (1L : 4SF) and 67% water by total mixture weight.



A) For different spacings and (2B) depth of grouting points.

B) For different spacings and (3B) depth of grouting points.

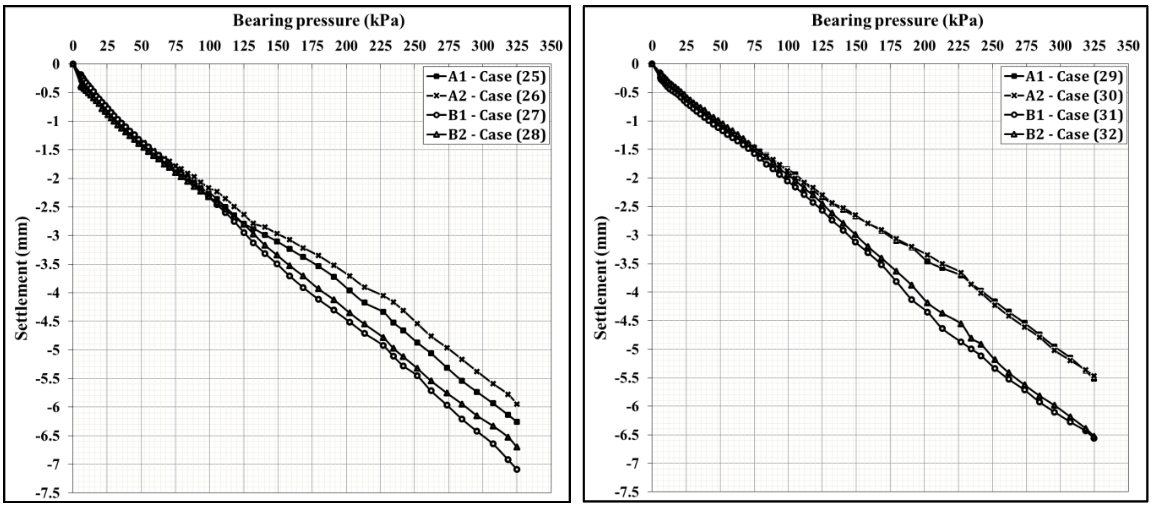
Figure 12 Bearing pressure-settlement curves of footing resting on dune sands stabilized by grouting with 33% (2L: 4SF) and 67% water by total mixture weight.



A) For different spacings and (2B) depth of grouting points.

B) For different spacings and (3B) depth of grouting points.

Figure 13 Bearing pressure-settlement curves of footing resting on dune sands stabilized by grouting with 33% (3L : 4SF) and 67% water by total mixture weight.



A) For different spacings and (2B) depth of grouting points.

B) For different spacings and (3B) depth of grouting points.

Figure 14 Bearing pressure-settlement curves of footing resting on dune sands stabilized by grouting with 25% (3L : 4SF) and 75% water by total mixture weight.

It is clear from Figures 17 to 20 that the ultimate bearing capacity of the footing increases with depth of grouting reaching a plateau at depth of about (2.5 B). At this depth, the effect of grouting diminishes due to small amount of foundation stresses reaching this depth.

Figures 21 to 24 show that the ultimate bearing capacity of the footing increases with No. of grouting points. When the No. of points becomes large (> 50), there will be inverse effect; the bearing capacity starts to decrease. The grout material fills the voids between sand particles, but when the grout volume exceeds the voids, it will cause spreading of volume particles, increase the void ratio and decrease the density and hence the shear strength.

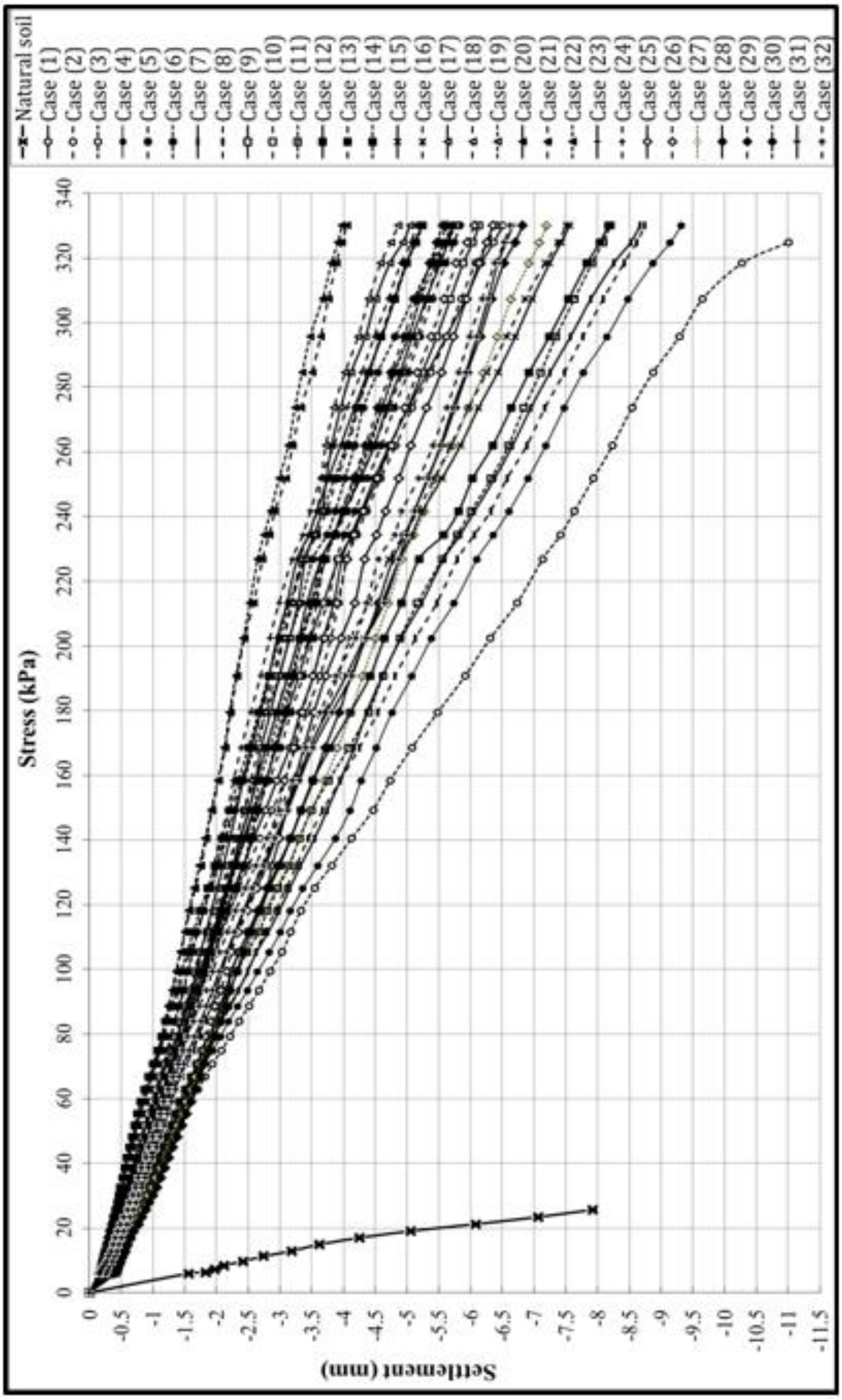


Figure 15 Bearing pressure-settlement curves of footing resting on natural soil and dune sands stabilized.

a. b.

Figure 16 Grouting behavior and the resulted jet-grouting piles after excavation.

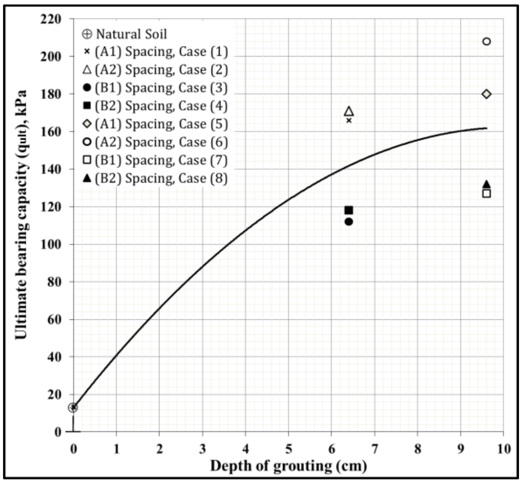


Figure 17 Ultimate bearing capacity – depth of grouting relationship for different spacings of dune sands stabilized by grouting with 33% (1L: 4SF) and 67% water by total mixture weight.

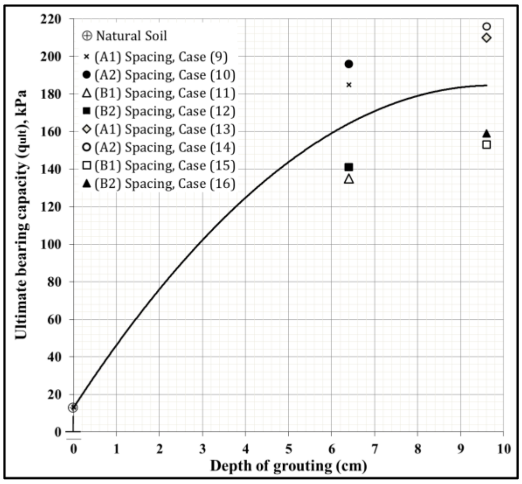


Figure 18 Ultimate bearing capacity – depth of grouting relationship for different spacings of dune sands stabilized by grouting with 33% (2L : 4SF) and 67% water by total mixture weight.

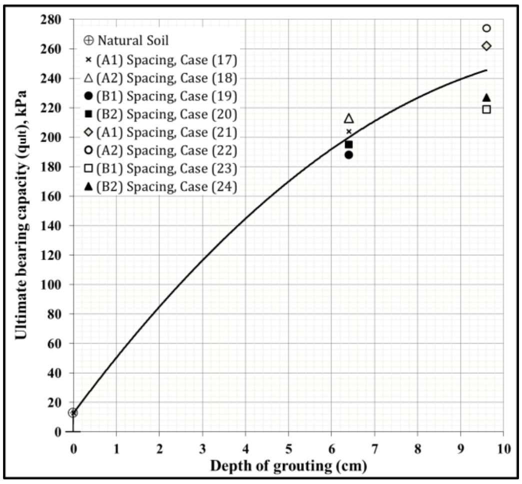


Figure 19 Ultimate bearing capacity – depth of grouting relationship for different spacings of dune sands stabilized by grouting with 33% (3L : 4SF) and 67% water by total mixture weight.

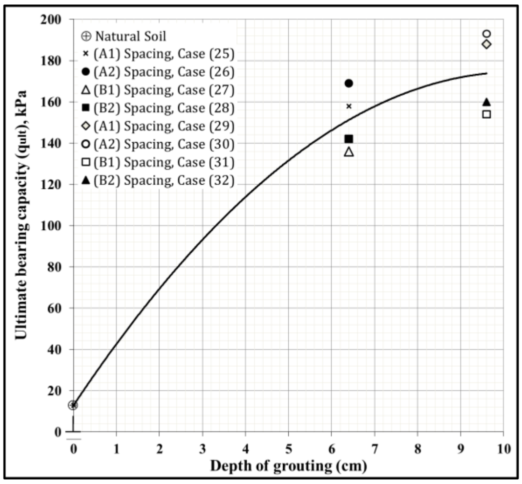


Figure 20 Ultimate bearing capacity – depth of grouting relationship for different spacings of dune sands stabilized by grouting with 25% (3L : 4SF) and 75% water by total mixture weight.

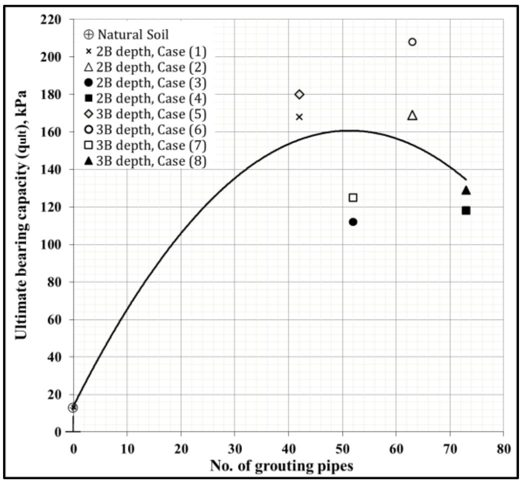


Figure 21 Ultimate bearing capacity – No. of grouting pipes relationship for different spacings and grouting depth of dune sands stabilized by grouting with 33% (1L : 4SF) and 67% water by total mixture weight.

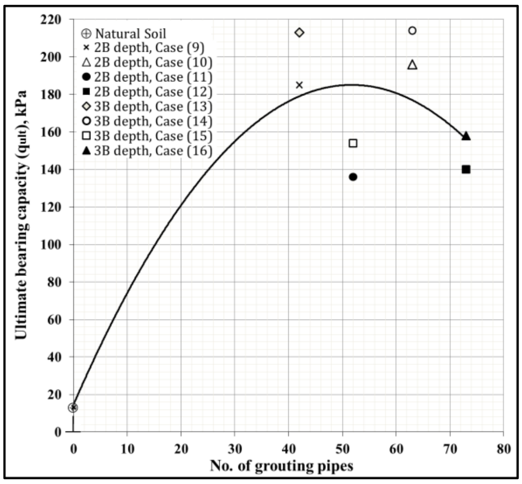


Figure 22 Ultimate bearing capacity – No. of grouting pipes relationship for different spacings and grouting depth of dune sands stabilized by grouting with 33% (2L : 4SF) and 67% water by total mixture weight.

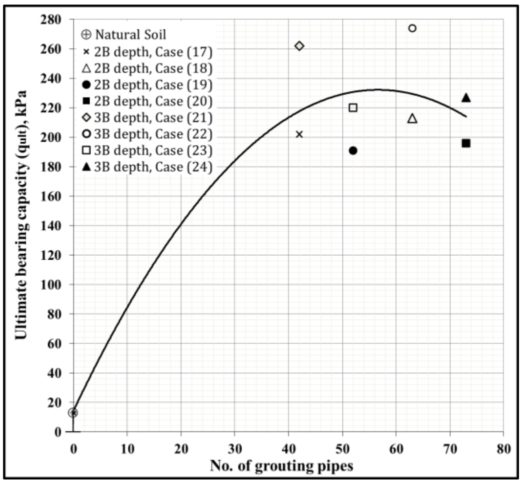


Figure 23 Ultimate bearing capacity – No. of grouting pipes relationship for different spacings and grouting depth of dune sands stabilized by grouting with 33% (3L: 4SF) and 67% water by total mixture weight.

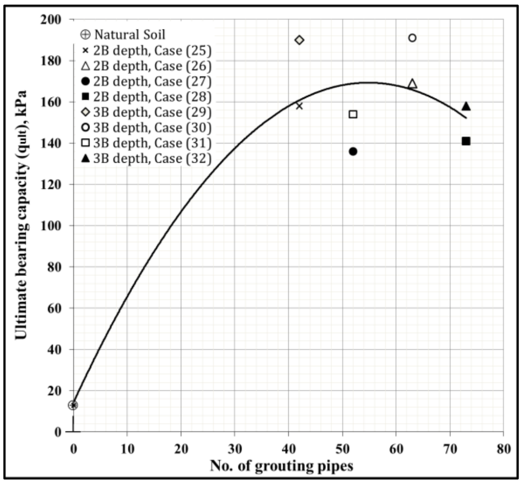


Figure 24 Ultimate bearing capacity – No. of grouting pipes relationship for different spacings and grouting depth of dune sands stabilized by grouting with 25% (3L: 4SF) and 75% water by total mixture weight.

CONCLUSIONS

The following conclusions are limited to the materials used and test conditions under which the tests were conducted. Based on the results obtained from this research work, the following conclusions can be made:

1. Baiji sand dunes are predominantly fine, poorly graded silica sand (91%) with small fines (9%) and non-plastic in character. Comparatively Baiji dune sands are clean fine aggregates with little aggressive components such as sulphates. Small difference can be noticed between the maximum and minimum unit weights. The method used to determine the unit weight of the dune sand showed considerable difference. Vibration can be very effective in compacting dry dune sand.
2. When the dune sand underneath and around a footing is injected by a slurry of lime-silica fume, there will be an increase in the ultimate bearing capacity of about 19

times. The bearing capacity increases with increase of depth of grouting holes around the footing area due to increase in L-SF grout, for a stabilizer grout percent of (33% (3L: 4SF) with 67% water by total mixture weight).

3. The ultimate bearing capacity of the footing increases with depth of grouting reaching a plateau at depth of about (2.5 B). At this depth, the effect of grouting diminishes due to small amount of foundation stresses reaching this depth.
4. The ultimate bearing capacity of the footing increases with No. of grouting points. When the No. of points becomes large (> 50), there will be inverse effect; the bearing capacity starts to decrease.

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